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On prediction of re-entry time of an upper stage from GTO

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Abstract

The evolution of objects in geostationary transfer orbit (GTO) is determined by a complex interplay of atmospheric drag and luni-solar gravity. These orbits are highly eccentric (eccentricity >0.7) and have large variations in velocity and perturbations during a revolution. The periodic changes in the perigee altitudes of these orbits are mainly due to the gravitational perturbations of the Sun and the Moon. The re-entry time of the objects in such orbits is sensitive to the initial conditions. The aim of this paper is to study the re-entry time of the cryogenic stage of the Indian geo-synchronous launch vehicle, GSLV-F04/CS, which has been decaying since 2 September 2007 from initial orbit with eccentricity equal to 0.706. Two parameters, initial eccentricity and ballistic coefficient, are chosen for optimal estimation. It is known that the errors are more in eccentricity for the observations based on two line elements (TLEs). These two parameters are computed with response surface method using a genetic algorithm for the selected eight different zones, based on rough linear variation of the mean apogee altitude during 200 days orbit evolution. The study shows that the GSLV-F04/CS will re-enter between 5 December 2010 and 7 January 2011. The methodology is also applied to study the re-entry of six decayed objects (cryogenic stages of GSLV and Molniya satellites). Good agreement is noticed between the actual and the predicted re-entry times. The absolute percentage error in re-entry prediction time for all the six objects is found to be less than 7%. The present methodology is being adopted at Vikram Sarabhai Space Centre (VSSC) to predict the re-entry time of GSLV-F04/CS.
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Keywords: High eccentric orbit; Response surface method; Genetic algorithm; Mean apogee altitude; Osculating eccentricity; Ballistic coefficient

1. Introduction

A stable space debris environment is defined as an environment permitting safe space operations in the long-term future (Klinkrad, 2006). As per Inter Agency Space Debris Co-ordination Committee (IADC) guidelines, one of the ways to achieve a stable space debris environment is to limit the lifetime of man-made orbiting vehicles to 25 years (ESA space debris mitigation handbook, 1999). Minimization of spent stage lifetime is one important objective in space debris mitigation efforts. Measures like de-boosting, compromise the payload capacity of the launch vehicles. The decay of the spent stages must be carefully monitored and analyzed to facilitate the enhanced planning for future missions. The geostationary transfer orbit (GTO) is a highly eccentric orbit with perigee normally at low altitudes (170–650 km) and the apogee near geo-stationary altitude (35,780 km). The orbital evolution along a GTO is sensitive to the initial conditions (Sharma et al., 2004). A spent stage in a GTO traverses the region between geostationary orbit and low-Earth orbit. Because geostationary orbit and low-Earth orbit are both densely populated orbit regimes, a GTO object likely has a higher probability of collision than an object on a near-circular orbit in either of these two regimes. The impact of the natural forces, such as drag and luni-solar perturbations, on the lifetime of high eccentricity orbits is the subject of earlier studies (King-Hele, 1975, 1982, 1987; Flury et al., 1992; Siebold and Reynolds, 1995; Klinkrad, 1999; Sharma et al., 2004). The effectiveness of luni-solar perturbations in reducing the lifetime of eccentric orbits with high apogee altitudes is also the subject of previous investigations (Klinkrad, 2006). Recently,

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the authors studied the re-entry of the GSLV-F01/CS (Mutyalarao and Sharma, 2010).

In this paper, we present a method to carry out the re-entry predictions of spent stages from GTO as an optimal estimation problem. Using this method we predict the re-entry time of the cryogenic stage (CS) of the Indian geosynchronous launch vehicle GSLV-F04/CS, employing the orbital data of CS in the form of two line element sets (TLEs), which are downloaded from http://www.space-track.org during 2 August 2009 to 11 March 2010. An accurate re-entry time prediction requires a good estimate of initial state. The semi-major axis of the initial orbit is often better known than the eccentricity, because the semi-major axis is directly related to orbital period, which is an easily measurable parameter. Eccentricity and ballistic coefficient are chosen as uncertain parameters for estimation. During the above period, eight time intervals are chosen based on rough linear variation of mean apogee altitude, for a detailed re-entry study. The response surface method (Myers and Montgomery, 1995) with genetic algorithm (GA) is applied to determine the optimal initial estimates of eccentricity and ballistic coefficient using the TLEs of each time interval. The re-entry time estimation in each case is computed using Numerical Prediction of Orbital Events (NPOE) software (http://www.cdeagle.com/html/npoe.html). This methodology is also applied to the six objects that have already decayed (three cryogenic stages of GSLV and three Molniya satellites).

2. Methodology

An accurate prediction of re-entry time of the rocket body from GTO requires a good estimate of the initial state. Of the two important orbital parameters needed for accurate re-entry time prediction, the semi-major axis of the initial orbit is better known than the eccentricity as it is directly related to the orbital period, which is an easily measurable parameter. We treat the eccentricity as an uncertain parameter in the present study. The ballistic coefficient, $B = m/C_DA$, kg/m^2, is treated as an uncertain parameter as well. B depends on the mass of the object, m, the drag coefficient, C_D, and the effective area, A. Of these parameters, C_D and A have significant uncertainties. In the present study, a good estimate of the initial values of the eccentricity and the ballistic coefficient from different epoch results in accurate predictions of re-entry times of the rocket body decaying from GTO.

The response surface methodology (RSM) is a collection of mathematical and statistical techniques developed by Box and Wilson (1951). It is useful for modeling and analysis of problems where the response is influenced by several variables (Myers and Montgomery, 1995), called design variables, and the objective is to optimize the response. Earlier investigations (Sharma et al., 2006) predicted the lifetime of the cryogenic spent stages of GSLV-D2 by combining the RSM with a genetic algorithm (GA) by employing the two line element sets (TLEs) over a period of 250 days. The TLE consists of two lines of formatted text. It provides the mean orbital elements with Simplified General Perturbations (SGP4/SDP4) that describe the orbit of Earth satellite at a specified epoch. The TLE format also provides the first and second time derivatives of the mean motion along with the ballistic drag terms of the satellite. The mean elements obtained from TLEs are converted into osculating elements by including the long- and short-periodic variations using SGP4/SDP4 orbit theories (Hoots et al., 1980; Vallado et al., 2006). SGP4 theory includes secular effects of J_2, J_4, J_2^2, long-periodic effects of J_2, J_3 and short-periodic effects of J_2 truncated to zeroth-order in eccentricity. For an orbit with the time period less than 225 min, SGP4 theory is employed to obtain the state vector at a specified epoch. Otherwise SDP4 theory is used to obtain the state vector. SDP4 theory includes all the terms of SGP4 plus the Earth's tesseral terms (2, 2), (3, 2), (5, 2), (4, 4), (5, 4) and the first-order luni-solar point mass gravity effects. The state vectors using SDP4 consisting of position and velocity, are obtained from the TLE using the SDP4 theory. These state vectors are used in the NPOE software to obtain the osculating and mean orbital elements at the initial state for the purpose of orbit propagation. This study considers two uncertain parameters: osculating eccentricity (e) and ballistic coefficient (B) as design variables and estimates the initial values of these two parameters. The re-entry bounds are computed by considering 10% variations in ballistic coefficient, solar flux ($F_{10.7}$) and geomagnetic index (A_p). Recently, the authors (Mutyalarao and Sharma, 2010) estimated the reentry time of an upper stage (GSLV-F01) from GTO from different epochs by the response surface method with a genetic algorithm with the TLEs available during the last one and a half months. In that study also optimal estimation of initial eccentricity and ballistic coefficient was made. The method was found to be an improvement over the least square method. In the present paper, the re-entry time estimation of GSLV-F04/CS is attempted based on rough linear variation of mean apogee altitude during the selected time intervals, using the above methodology for estimating the initial eccentricity and ballistic coefficient in each interval.

2.1. Response surface methodology

As previously mentioned, RSM is a collection of mathematical and statistical techniques that is useful for modeling and analysis of problems where the response is influenced by several variables (Myers and Montgomery, 1995) called design variables, and the objective is to optimize the response. Suppose x_1 and x_2 are two independent design variables with the response y depending on them. The response can be expressed as

$$y = f(x_1, x_2) + \varepsilon, \tag{1}$$

where the error term ε represents any measurement error on the response, as well as other types of variations not counted in f. It is a statistical error that is assumed to distribute normally with zero mean and variance s^2. In most RSM problems, the true response function *f* is unknown. For obtaining an approximation for *f*, a low-order polynomial is used initially. If the response can be defined by a linear function of independent variables, then the approximating function is a first-order model. If there is a curvature in the response surface, then a higher degree polynomial should be used. In order to obtain the approximation of polynomials, an experimental design (Oehlert, 2000) must be used to collect the response data. Once the data are collected, the method of least squares (Conte and De Boor, 2000) is used to estimate the parameters in the polynomials. The response surface analysis is performed by using the fitted surface.

We use initial osculating eccentricity (e) and ballistic coefficient (*B*) as the design variables to update the knowledge of the initial state. The propagated mean apogee altitude for the specified initial osculating eccentricity and ballistic coefficient is referred to here as "mean apogee surface". It may be noted that the variations of the mean apogee surface reflect the dynamics of the orbital motion. The present methodology is as follows:

The mean orbital elements are obtained from TLEs. We call them observed values. The time intervals based on rough linear variation of mean apogee altitude are considered. Each time interval is referred as a "zone". The osculating orbital elements at the initial epoch of each zone are obtained with the help of the SGP4/SDP4 theories (Hoots and Roehrich, 1980; Vallado et al., 2006). We select three initial values of the osculating eccentricity (e_1, e_2, e_3) and ballistic coefficient (b_1, b_2, b_3) in such a way that the observed mean apogee altitudes during the interval of time considered in our study fall well within the lower and the upper bounds of the mean apogee surfaces.

(1) With the selected initial values of *e* and *B*, we generate nine mean apogee surfaces. Each surface is generated by propagating the trajectory with the selected initial values of *e* and *B* using NPOE. These mean apogee surfaces are used to compute the predicted mean apogee altitude at a specified epoch by a method of interpolation (Conte and De Boor, 2000).

(2) A genetic algorithm (Michalewicz, 1996) is employed in the present study to estimate the initial values of *e* and *B* which minimize the root-mean-square error between the observed and the predicted mean apogee altitudes. Here the computation of optimal estimates of *e* and *B* is carried out by setting the tolerance on optimality to 7 km. The population size is selected to be 100. Because all optimization parameters have a specified range, a binary coded GA is utilized and all parameters are coded in 60 bits. A single point crossover with probability of 0.8, and bit-wise mutation with probability of 0.01 are selected. The GA is run for 100 generations after experimentation.

The justification for using RSM to predict mean apogee altitude, as opposed to using NPOE software to propagate the trajectory forward (starting with the initial values of *e* and *B* possessed by each population member in the GA) to the observed epoch time of the TLE, is the computational savings of interpolation over numerical propagation.

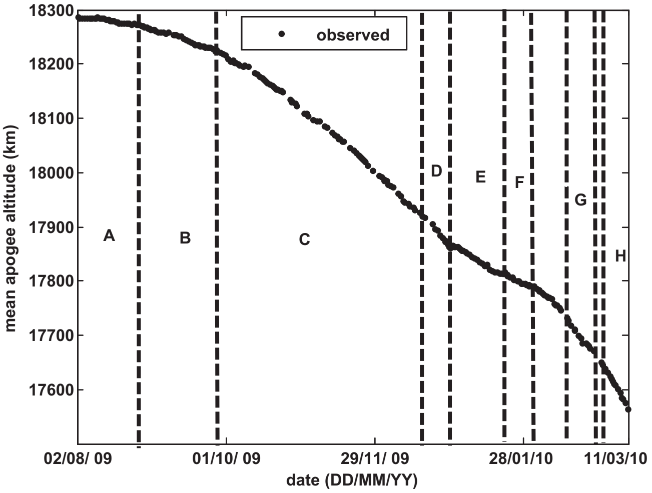

Fig. 1. Variation of mean apogee altitude of GSLV-F04/CS (NORAD No. 32051) with each zone label mentioned.

2.2. Prediction of re-entry time for GSLV-F04/CS

The mean apogee and the mean perigee altitudes of the rocket body computed from the TLEs from 2 August 2009 to 11 March 2010 are plotted in Figs. 1 and 2, respectively. Eight zones (labeled *A*, *B*, *C* ... *H*) between 2 August 2009 and 11 March 2010 are chosen mainly based on rough linear variation of mean apogee altitude. Using the above methodology, the estimation of the initial ballistic coefficient and the initial osculating eccentricity is made for each zone. Using the estimated values of *e* and *B* and keeping all other orbital elements unchanged, the re-entry time is calculated using NPOE. The rocket body is assumed to have

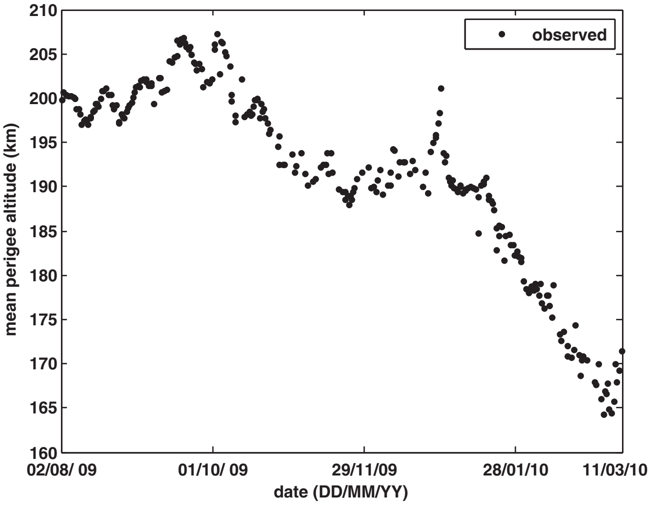

Fig. 2. Variation of mean perigee altitude GSLV-F04/CS (NORAD No. 32051).

Table 1
Computed values of initial osculating eccentricity and initial ballistic coefficient along with re-entry time in each zone.

Zone label	TLEs considered (UTC)		Computed values		Predicted reentry time (UTC)[a]	Time interval[b] (days)	Mean deviation[c] (days)
	From	To	Initial osculating eccentricity (e)	Initial ballistic coefficient (kg/m^2)			
A	02/08/09 15:45:30	25/08/09 08:30:40	0.57928426	256.0590001	06/12/10 00:05:00	490.34	−16.5036
B	25/08/09 08:30:40	29/09/09 06:40:57	0.57889926	129.2699591	05/12/10 16:30:00	490.0309	−16.8195
C	29/09/09 06:40:57	20/12/09 13:44:30	0.57794232	59.49630780	07/01/11 09:30:00	522.73	15.8888
D	20/12/09 13:44:30	31/12/09 05:08:49	0.57520681	49.57082347	30/12/10 22:04:00	515.2628	8.4124
E	31/12/09 05:08:49	19/01/10 14:37:04	0.57467718	89.22781823	02/01/11 19:48:00	518.1684	11.3180
F	19/01/10 14:37:04	07/02/10 12:31:01	0.57435027	135.4438362	23/12/10 16:27:00	508.0288	1.1784
G	12/02/10 13:32:46	21/02/10 12:42:04	0.57327266	81.43612833	19/12/10 04:22:00	503.5253	−3.3251
H	01/03/10 14:15:09	11/03/10 03:30:13	0.5718824	92.28161084	22/12/10 08:35:00	506.7010	−0.1494

[a] UTC Coordinated Universal Time: day(DD)/month(MM)/year(YY) hour(HH): minutes(MM): seconds(SS).
[b] Time intervals calculated as the number of days between the re-entry prediction and the first TLE epoch of zone A.
[c] Deviation of time interval column from the average over all eight values.

reentered the atmosphere as soon as the mean perigee altitude decreases to 10 km, and the re-entry time corresponds to this re-entry condition. The force model used includes terms up to $J_{10,\ 10}$ of the Earth's gravity model based on GEM10B (Lerch et al., 1981), atmospheric drag perturbations and lunar and solar gravity effects. The MSIS90 density model (Hedin, 1991) including the daily values of $F_{10.7}$ and A_p is used in NPOE to compute the drag force. Table 1 provides the zones considered, estimated values of B, e, predicted re-entry time from the initial epoch of each zone, the time interval between the predicted re-entry time and a chosen epoch (i.e., time of the first TLE epoch used in zone A) and the deviation of the time interval from the average over all eight values. The results across the eight zones are seen to be very consistent, as indicated by the small deviations of each predicted re-entry time from the average. From Table 1, two cases are chosen for illustrating the details of the employed methodology. These cases are described in the section below.

2.3. Case studies

2.3.1. Zone B

The osculating orbital elements of GSLV-F04/CS as obtained from a TLE on 25 August 2009 08:30:40(UTC) [Coordinated Universal Time (UTC)] are:

Semi-major axis (km) = 15611.934860.
Eccentricity = 0.578899.
Inclination (°) = 15.99310.
Argument of perigee (°) = 117.18156.
Right ascension of the ascending node (°) = 295.75908.
True anomaly (°) = 242.76514.

In order to generate a set of mean apogee surfaces in initial osculating eccentricity and ballistic coefficient phase space, three values of initial osculating eccentricity (0.578899, 0.578999, 0.579099) and three values of the ballistic coefficient (127, 147, 167) are selected to obtain nine grid points. Fig. 3 depicts these nine mean apogee surfaces. A genetic algorithm is applied to estimate the osculating eccentricity and ballistic coefficient at the initial epoch by minimizing the error between the observed and predicted mean apogee altitudes in the zone considered. The values of e and B obtained are 0.578899260 and 129.2699591 kg/m^2, respectively. Using these values, Fig. 4 depicts the comparison of observed and predicted mean-apogee altitudes along with the error for the zone B. It is found that the error (=predicted mean apogee altitude-observed mean apogee altitude) is less than 3 km in 35 days against a decrease of 53.226 km. With the estimated values of e and B and with the monthly predicted values of $F_{10.7}$ and A_p, the re-entry epoch of GSLV-F04/CS is found to be 5 December 2010 16:30 (UTC).

2.3.2. Zone E

The osculating orbital elements of GSLV-F04/CS as obtained from a TLE on 31December 2009 05:08:49(UTC) are:

Semi-major axis (km) = 15438.066771.
Eccentricity = 0.574689.

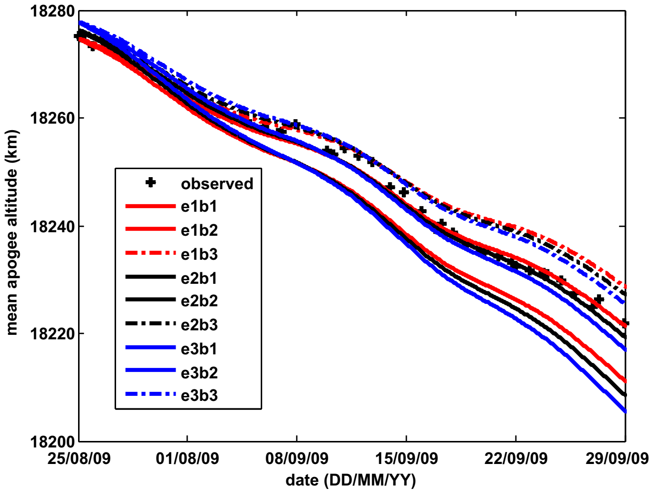

Fig. 3. Set of mean apogee surfaces for zone B with $(e_1, e_2, e_3) = (0.578899, 0.578999, 0.579099)$ and $(b_1, b_2, b_3) = (127, 147, 167)$.

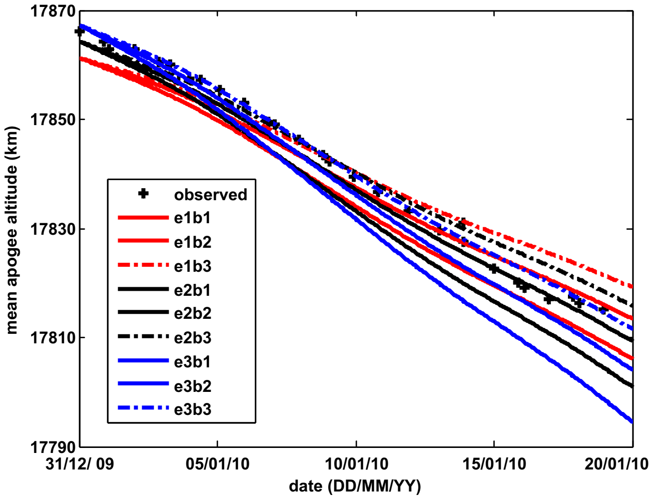

Fig. 5. Set of mean apogee surfaces for zone E with $(e_1, e_2, e_3) = (0.574489, 0.574689, 0.574889)$ and $(b_1, b_2, b_3) = (75, 85, 95)$.

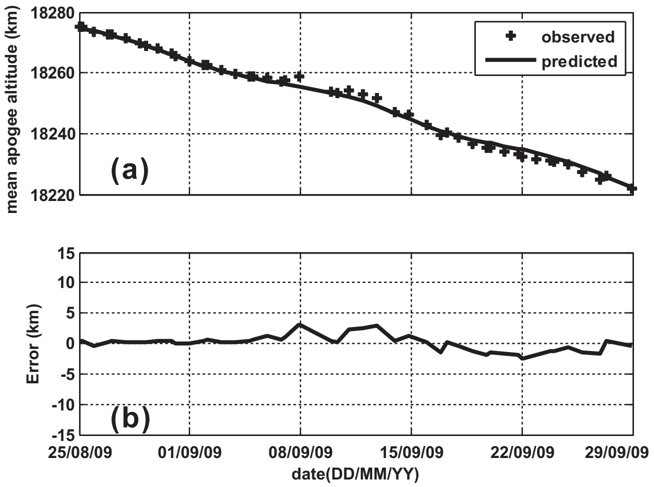

Fig. 4. The variation of mean apogee altitude for zone *B*, using optimal values of *e* and *B*. (a) comparison of observed and predicted mean apogee altitudes; (b) error (=predicted mean apogee altitude-observed mean apogee altitude).

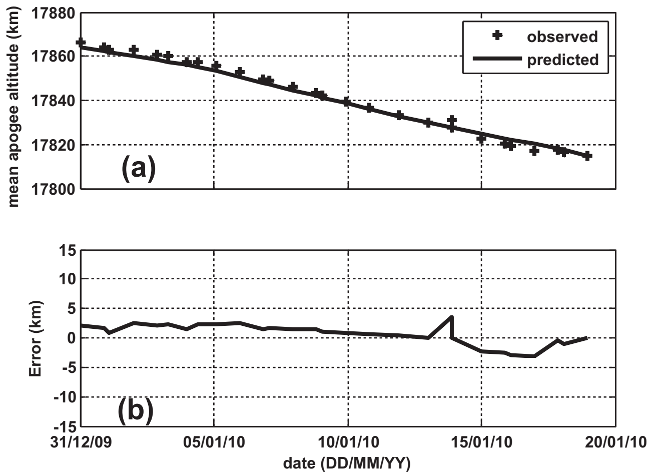

Fig. 6. The variation of mean apogee altitude for zone *E* using optimal values of *e* and *B*. (a) Comparison of observed and predicted mean apogee altitudes; (b) error (=predicted mean apogee altitude-observed mean apogee altitude).

Inclination (°) = 15.96512.
Argument of perigee (°) = 348.64617.
Right ascension of the ascending node (°) = 172.70659.
True anomaly (°) = 10.48353.

As discussed in Section 2.3.1, here the three values of osculating eccentricity (0.574489, 0.574689, 0.574889) and three values of ballistic coefficient (75, 85, 95) are selected to obtain nine grid points. Fig. 5 depicts these nine mean apogee surfaces. Using the genetic algorithm, the values of *e* and *B* obtained are 0.57467718 and 89.22781823 kg/m^2, respectively. Fig. 6 depicts the comparison of observed and predicted mean apogee altitudes along with the error for the zone E. In this case the error is found to be less than 3.6 km in 19 days against a decrease of 51.09 km. The re-entry epoch of GSLV- F04/CS, with the estimated values of e and B and with the monthly predicted values of $F_{10.7}$ and A_p, is 2 January 2011 19:48 (UTC).

3. Prediction of re-entry time for some other decayed objects

Six objects among which three rocket bodies namely GSLV-D1/CS (NORAD No. 26746), GSLV-D2/CS (NORAD No. 27808), GSLV-F01/CS (NORAD No. 28418) and three satellites namely Molniya3-34 (NORAD No. 19713), Molniya3-46 (NORAD No. 23211), Molniya3-39 (NORAD No. 20813) are considered to predict the re-entry time by using the present methodology. A total of seven zones are considered to predict the re-entry time of these objects. Table 2 provides the time interval of the TLEs considered for each zone along with the computed initial values of the osculating eccentricity (e), ballistic

Table 2
Comparison of actual and predicted reentry epoch of some decayed objects by using the computed values of e and B.

Zone label	TLEs considered (UTC)		Computed values		Predicted re-entry time (UTC)	% Error
	From	To	Initial osculating eccentricity (e)	Initial ballistic coefficient (*B*)		
GSLV D1/CS (NORAD No. 26746) actual re-entry:18/01/03 05:31 UTC						
I	22/12/02 17:45:30	31/12/02 17:47:19	0.37468978	93.13786894	17/01/03 02:25	−6.46
GSLV D2/CS (NORAD No. 27808) actual re-entry:24/02/05 17:24 UTC						
II	19/01/05 17:13:34	29/01/05 09:59:57	0.39534279	97.99438216	23/02/05 02:43	−6.13
GSLV-F01/CS (NORAD No. 28418) actual re-entry:24/11/07 19:300 UTC						
IIIa	15/07/07 23:17:41	12/08/07 01:24:46	0.5390412	72.146125132	25/11/07 07:17	0.47
IIIb	06/10/07 05:41:37	14/10/07 11:15:18	0.40580561	81.87754181	24/11/07 23:59	0.45
Molniya3-34(NORAD No. 19713)re-entry: 27/05/07 07:17 UTC						
IV	17/05/07 03:39:08	20/05/07 19:15:36	0.55847152	168.26991032	27/05/07 07:39	0.24
Molniya3-46(NORAD No. 23211)re-entry: 10/02/09 13:18 UTC						
V	30/01/09 14:49:33	02/02/09 16:00:38	0.47445539	42.75788298	10/02/09 07:38	−2.99
Molniya3-39(NORAD No. 20813)re-entry: 08/07/09 22:49 UTC						
VI	29/06/09 05:21:12	4/07/09 03:05:12	0.54609431	1250.87636707	08/07/09 17:31	−4.58
			Root-sum-square (RSS) of (%) error			10.4741

$^{\$}\text{percentage error} = \frac{(\text{predicted re-entry time}-\text{actual re-entry time})}{(\text{actual re-entry time}-\text{time of the latest TLE epoch used})} \times 100.$

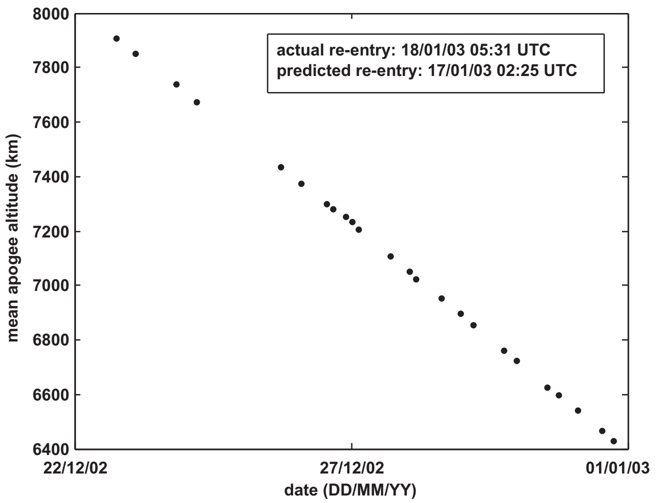

Fig. 7. Variation of mean apogee altitude of GSLV-D1/CS (NORAD No. 26746) in zone I.

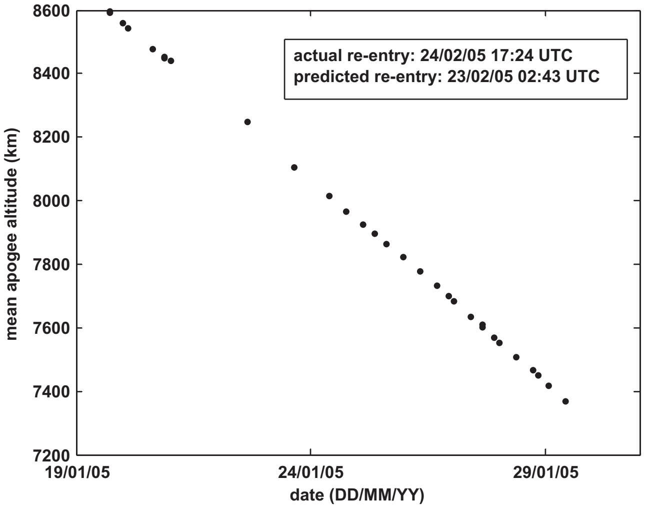

Fig. 8. Variation of mean apogee altitude of GSLV-D2/CS (NORAD No. 27808) in zone II.

coefficient (B), predicted re-entry time and percentage error [=((predicted re-entry time – actual re-entry time)/(actual re-entry time – time of the last TLE epoch in the zone)) × 100] for each prediction. It is noted that the absolute value of percentage error in all the predictions is less than 7%. Figs. 7-12 show the variation of mean apogee altitude for each zone.

Since the present methodology involves two parameters; the osculating eccentricity (*e*) and ballistic coefficient (*B*) to update the knowledge of the initial state available from the TLE, a study is carried out to bring out the effect of *e* and *B* on re-entry estimates. In this study NPOE software is used to propagate the trajectory starting from the initial TLE epoch. The propagation is carried out using the values of

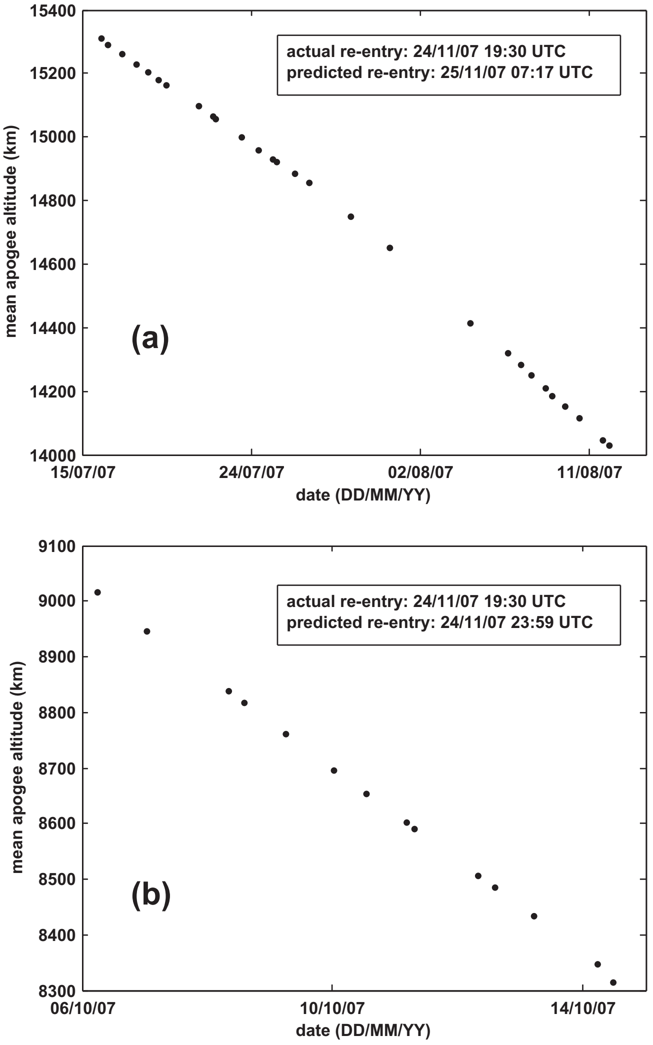

Fig. 9. Variation of mean apogee altitude of GSLV-F01/CS (NORAD No. 28418) in each zone (a) zone IIIa; (b) zone IIIb.

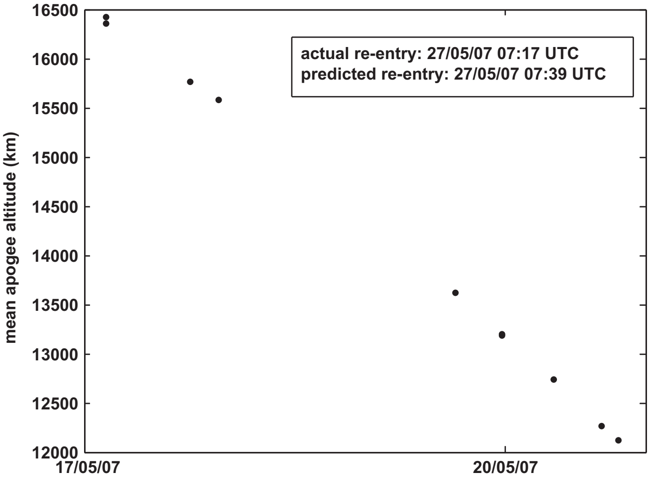

Fig. 10. Variation of mean apogee altitude of Molniya3-34 (NORAD No. 19713) satellite in zone IV.

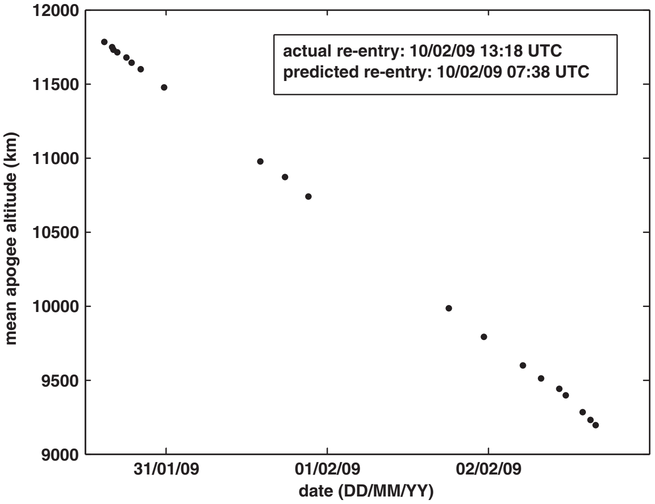

Fig. 11. Variation of mean apogee altitude of Molniya3-46 (NORAD No. 23211) satellite in zone V.

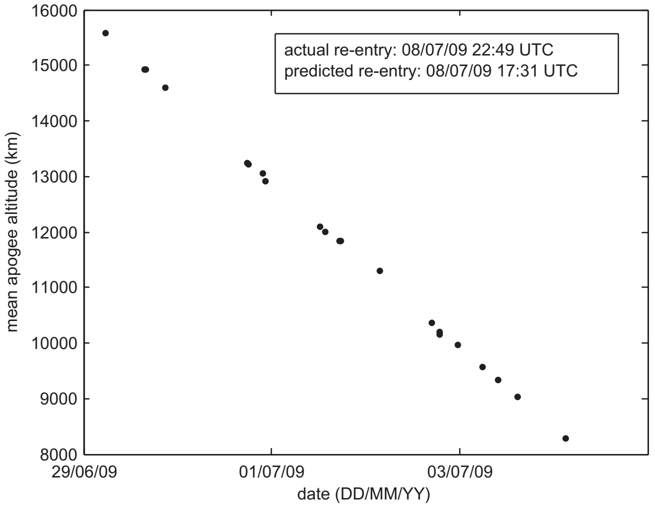

Fig. 12. Variation of mean apogee altitude of Molniya3-39 (NORAD No. 20813) satellite in zone VI.

e and *B* from three cases. The three cases include: neither *e* nor *B* optimized, only *e* optimized and only *B* optimized. Table 3 provides the comparison of the predictions of re-entry time for all the six decayed objects in these three cases. Note that the case where either *e* or *B* is optimized alone actually results in a higher root-sum-square (RSS) percentage error than when neither *e* nor *B* is optimized. Yet, the case where both *e* and *B* are optimized results in the lowest RSS percentage error of all (10.4741 as seen from Table 2). Specifically, of the seven different zones considered, the case of optimizing both *e* and *B* yields a lower percentage error than optimizing neither *e* nor *B* in all but

Table 3
Comparison of predicted reentry time of six decayed objects in three cases. The three cases are *X*: neither initial osculating eccentricity (e) nor initial ballistic coefficient (B) optimized; *Y*: Only e optimized; *Z*: Only *B* optimized.

Zone label	Case: *X*		Case: *Y*		Case: *Z*	
	Predicted re-entry time (UTC)	% Error	Predicted re-entry time (UTC)	% Error	Predicted re-entry time (UTC)	% Error
I	17/01/03 00:03	−7.02	17/01/03 16:03	−3.21	16/01/03 16:09	−8.90
II	23/02/05 15:57	−4.03	26/02/05 16:21	7.44	20/02/05 20:10	−14.77
IIIa	25/11/07 05:46	0.41	25/11/07 07:52	0.49	25/11/07 06:04	0.42
IIIb	19/11/07 12:21	−12.81	25/11/07 12:24	1.70	19/11/07 02:31	−13.81
IV	27/05/07 20:23	8.40	27/05/07 17:39	6.64	27/05/07 20:43	8.61
V	09/02/09 22:39	−7.74	08/02/09 18:48	−22.45	11/02/09 20:31	16.49
VI	08/07/09 01:09	−18.72	07/07/09 16:08	−26.51	09/07/09 03:00	3.62
Root-sum-square (RSS) of % error	26.6588		36.3271		29.1103	

one of the zones. While the present methodology is not guaranteed to improve re-entry estimates in every scenario, these results indicate that the RSM technique combined with a GA is a promising approach.

4. Conclusions

The orbital lifetime of a GSLV-F04/CS rocket body is estimated with the help of the response surface method with the genetic algorithm, which is utilized for estimating the initial values of the osculating eccentricity and the ballistic coefficient from eight selected time intervals based on rough linear variation of mean apogee altitude. NPOE software is utilized for orbit propagation. The absolute value of the mean deviation is found to be less than 16.82 days in the lifetime estimation of GSLV-F04/CS. The method is also applied to predict the re-entry time of six other decayed objects from high eccentric orbits. Generally, the present methodology is seen to improve the agreement between the actual and predicted re-entry times, yielding an absolute error value of less than 7% in all cases.

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